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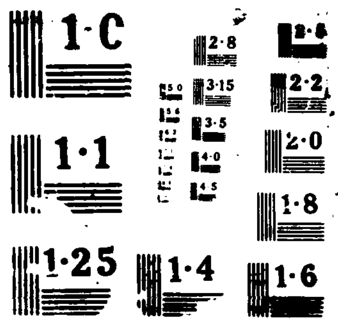
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ROYAL SIGNALS AND RADAR ESTABLISHMENT

Memorandum 4039

TITLE DIFFRACTION BY A SIMPLE DEEP PHASE OBJECT

AUTHORS D L JORDAN, R C HOLLINS, E JAKEMAN, P J TUFTON

DATE MAY 1987

SUMMARY

The work presented in this Memorandum is the first stage in a programme of work designed to study the scattering of radiation from simple phase objects that have dimensions smaller than the wavelength of the probing laser radiation. This initial work establishes the theory and supporting experimental evidence when the structure is somewhat larger than the probing wavelength.

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1. INTRODUCTION

With the continuing reduction in element size in integrated circuits, the point will eventually be reached when sizes become comparable or less than the wavelength of visible light. This raises fundamental questions about how to measure such structures. It is generally thought that conventional physical optics is inappropriate for dealing with objects having dimensions smaller than the probing wavelength. Consequently we have initiated a programme of work to study the scattering of radiation by sub-wavelength sized structures. In particular, we are concentrating on phase rather than amplitude objects because of their relevance to semiconductor large scale integration work.

For simplicity we have chosen a single groove as our target. A series of silicon slices have been prepared, each slice containing a series of etched equal depth grooves with nominal widths shown in Figure 1(a). Each groove, which was about 2.5mm long had a 100μm width groove perpendicular to it at each end to delineate it (Figure 1(b)). In all, four slices were used, having etching times of $\frac{1}{4}$ hour, $\frac{1}{2}$ hour, 1 hour and $1\frac{1}{2}$ hours; these corresponded to depths ranging from $\sim 4\mu$m to $\sim 30\mu$m. When illuminated by CO_2 laser radiation of wavelength 10.6μm the silicon grooves will allow the study of structures ranging from about twice to slightly less than half the wavelength to be conducted. Work is also in hand to produce grooves of dimensions of order 1μm.

Unlike the case for amplitude objects (eg slits) where there is a great wealth of theoretical and experimental work [1], there appears to be very little published work on simple phase objects. Consequently in this Memorandum we briefly outline the appropriate physical optics theory for structures large compared with the probing wavelength, then present some scattering measurements from the grooves using He-Ne laser light. For this case even the smallest groove ($\sim 4\mu$m) is many times the probing wavelength (0.63μm) and so the derived theory should apply. We then present some initial measurements made using a CO_2 laser, again with the slits wide compared to the laser radiation wavelength.

2. THEORY

The situation considered is that shown in Figure 2. A Gaussian profile beam of width W is incident on the groove of width s and depth d; for simplicity normal incidence is assumed. The incident radiation is diffracted at the top of the groove, reflected from the bottom and observed in the Fraunhofer region at an angle θ. The neglect of secondary diffraction at the bottom of the groove is justified when

$$\frac{kS^2\cos\theta}{2d} >> 1$$

ie when the bottom of the groove is in the near field of the diffraction pattern produced by the top of the groove. The phase difference corresponding to the path difference between rays AE and ABF is given by:-

$$AB + BC - AD = \frac{2\Phi_o}{\cos\theta} - 2\Phi_o \frac{\sin^2\theta}{\cos\theta} = 2\Phi_o \cos\theta$$

where Φ_o = kd and $k = 2\pi/\lambda$. The amplitude in the far field in direction θ is given by:

$$AF(\theta) \left\{ \int_{-\infty}^{-S/2} \exp\left[\frac{-x^2}{W^2}\right] \exp(ikx\sin\theta)dx + \int_{-S/2}^{S/2} \exp\left[\frac{-x^2}{W^2}\right] \right.$$

$$\exp i\,(kx \sin\theta + 2\Phi_o \cos\theta)dx \qquad (1)$$

$$\left. + \int_{S/2}^{\infty} \exp\left[\frac{-x^2}{W^2}\right] \exp(ikx \sin\theta)dx \right\}$$

where A is a complex constant and $F(\theta)$ is an angle dependent term which is unity for normal incidence. This expression can be written as:

$$\int_{-\infty}^{\infty} \exp\left[\frac{-x^2}{W^2}\right] \exp(ikx \sin\theta)dx + \int_{-S/2}^{S/2} \exp\left[\frac{-x^2}{W^2}\right] \exp(ikx \sin\theta) \qquad (2)$$

$$[\exp(2i\Phi_o \cos\theta)-1]dx$$

The first integral is the specular term and reduces to a narrow gaussian

$$\pi^{\frac{1}{2}} W \exp\left[\frac{-k^2 \sin^2\theta\, W^2}{4}\right] \qquad (3)$$

When S << W the second integral reduces to:

$$\left\{ \exp(2i\,\Phi_o \cos\theta) - 1 \right\} \left\{ \frac{S \sin\left[\frac{kS \sin\theta}{2}\right]}{\left[\frac{k\,S \sin\theta}{2}\right]} \right\} \qquad (4)$$

The first term is the amplitude variation due to the finite depth of the groove and the second is the effect due to the finite groove width. Hence the intensity in direction θ is proportional to:

$$2S^2 \{1-\cos(2\Phi_o \cos\theta)\} \frac{\sin^2 \left[\frac{kS\sin\theta}{2}\right]}{\left[\frac{kS\sin\theta}{2}\right]^2} \tag{5}$$

Consequently nulls occur due to the width of the groove in direction θ_n satisfying the condition

$$\frac{kS\sin\theta}{2} = n\pi \tag{6}$$

where n = 0, 1, 2 --- ie nulls occur at

$$\theta_n = \sin^{-1}\left[\frac{n\lambda}{S}\right] \tag{7}$$

Nulls also occur due to the finite depth of the groove, and occur when

$$2\Phi_o \cos\theta = 2\pi m \tag{8}$$

ie unlike the width term the nulls are equally spaced in cos θ, the separation between successive minima being:

$$\cos\theta_{m+1} - \cos\theta_m = \frac{\lambda}{2d} \tag{9}$$

If the angle of incidence is not zero but rather θ_i, then the position of width induced minima is changed to:

$$\sin\theta_n = \frac{n\lambda}{S} + \sin\theta_i \tag{10}$$

The separation between the depth induced minima remains as $\lambda/2d$. There is also an overall slow angular variation of the scattered intensity due to the factor $F(\theta)$ (equation 1) and the modified sin θ term in the denominator of (4); the overall factor is [2]

$$(\sin\theta_i - \sin\theta)^{-2} \left[\frac{1+\cos\theta_i\cos\theta - \sin\theta_i\sin\theta}{\cos\theta_i + \cos\theta}\right]^2$$

This does not however affect the position of the diffraction minima.

It should be emphasised that the result (9) predicts that the separation in $\cos\theta$ between the depth induced minima is $\lambda/2d$, and not λ/d as given by incorrectly assuming diffraction occurs at the base of the groove rather than at the top of it. The simple

result given here is also correct in the presence of multiple scattering. Figure 3(a) shows the limit of single scattering. Wave ABC just escapes the groove with a single scattering (at B). The simplest multiple scattering situation is shown in Figure 3(b). Ray ABCD undergoes one extra scattering compared with the situation shown in Figure 3(a). Since however AB = BE the situation is equivalent to a single scattering by ray EBCD and the previous arguments apply. A similar result can be shown to apply for all higher multiple scattering situations

3. EXPERIMENT

The experimental arrangement is as shown in Figure 4. The output from a He-Ne laser was chopped at ~ 500Hz before impinging on the silicon slice, the angle of incidence being 5.6°. For some of the measurements a lens was used to focus the radiation on the silicon groove to increase the measured signal-to-noise ratio. The detector was a 10mm diameter photodiode with a rectangular mask over its front surface. This allowed the vertical aperture to be kept at about 8mm so that as the detector was scanned around the silicon it did not 'walk-off' the one-dimensional diffraction pattern generated by the groove. The width of the aperture was kept in the range 2-4mm; below 2mm speckle noise became intrusive and above 4mm the angular resolution was compromised, the upper size of aperture corresponding to an angular resolution of about 0.3 degrees.

The detector was scanned via an arm attached to a computer controlled rotating table, the silicon being rigidly mounted through a hole in the centre of the table. The detector signal was fed through a low-noise amplifier into a phase sensitive detector and hence into a programmable digital voltmeter and finally into the computer controlling the table rotation. Typically 1000 readings were taken in a 30° scan. For each groove several experimental runs were taken with various amplifier gains, the detection system inevitably saturating near the specular beam position. To accurately determine the specular angle a run was made with an optical attenuator attached to the detector.

For the CO_2 measurements the He-Ne laser was replaced by a CW CO_2 laser of heavy invar construction for maximum passive stability; it produced a maximum of 3W of TEM_{00} power on the P20 (00°1 - 10°0) line. A dither stabilisation scheme was incorported into the laser to keep power fluctuations below 0.1%. A Brewster window was included in the cavity to ensure a well defined polarisation direction. The photodiode detector was replaced by a pyroelectric one. A rotatable wire grid polariser was attached to the front of the detector housing to allow the amount of depolarisation caused by the

groove to be determined. The plane of polarisation of the laser radiation incident on the groove could be rotated by means of a zinc selenide half wave plate between the laser and the silicon groove.

Figure 5 shows two typical He-Ne angular scans of the mean scattered intensity $\langle I(\theta)\rangle$ on a log - linear plot. The traces have been moved vertically to separate them and do not reflect differences in measured signals. Both traces have the same nominal width of $20\mu m$ but different depths, the top one being from the $\frac{1}{4}$ hour etched slice and the lower one from the $\frac{1}{2}$ hour one. Both traces display two obvious periods; the short 'sinusoidal-type' period can be attributed to the width of the groove and the longer period modulation to its depth.

Rather than just relying on the groove widths being exactly the same as that of the mask used to make them, the width of each groove was measured using a microscope. This showed that nominally identical widths on different slices were in fact slightly different, the widths being generally wider with increasing etching time. No variation of width along a groove was apparent. Figure 6 is a plot of the measured angular positions of the minima of the diffraction pattern from the 1 hour etch slice (using He-Ne radiation) versus that predicted from (10) using the measured widths. The crosses are from the $23.5\mu m$ wide groove (nominally $20\mu m$) and the circles are from the $7.3\mu m$ (nominally $4\mu m$) groove. The close agreement between these results and the predicted dotted line indicates that the theory is adequate. Similar results were found for all the other grooves including the $4\mu m$ nominal groove width, which was indeed actually $4\mu m$, on the $\frac{1}{4}$ hour etch slice.

The minima due to the groove depth are somewhat less well defined than those due to the width. This is principally due to non-uniformity in depth of any one groove. On any one silicon slice all the grooves and their adjacent $100\mu m$ wide delineation grooves should all be of equal depth. The actual depth was measured using an Alpha-Step profile measuring instrument scanned across one of the delineation grooves. In general the depth varied across the groove by anything up to $1\mu m$. The variation is presumably less across the much narrower grooves used in the experiment. However, under a microscope various apparently random depth variations could generally be seen along any one groove. Consequently it is likely that any groove will vary in depth by a significant fraction of the visible probing wavelength over its illuminated length ($20-1000\mu m$). Hence the diffraction minima can be expected to appear 'smoothed-out' to some degree, as found. The depth induced minima corresponding to the lower scans in Figure 5 are shown by arrows.

From plots such as those in Figure 5 the angles at which depth induced minima occurred were found by inspection. A check was made to see if successive minima were equally spaced in $\cos\theta$, and the mean depths and standard deviation calculated from (9). These calculated depths for nominally $20\mu m$ wide grooves are shown in Figure 7 plotted against the Alpha-Step measurements. The error bars on the Alpha-Step measurements encompass the depth variation measured across the $100\mu m$ delineation grooves. From this plot it can be seen that there is no evidence of any significant discrepancy between the depths determined using the scattering data and those measured using the profile measuring device. Similar results were found using the $4\mu m$ grooves.

The experiments were much more difficult to perform using a CO_2 laser. It is non trivial to align an invisible beam (infra-red) of a few tens of microns diameter onto the centre of a groove whose width is a few microns (which is difficult to see by eye) and then traverse the resulting weak and invisible one-dimensional diffraction pattern by a relatively small (mm) detector so as not to 'walk-off' the pattern. For most of the results presented below a lens was placed in front of the detector to increase the measured signal-to-noise ratio. An approximate Fraunhofer configuration was still however maintained.

Figure 8 is a plot of the measured angular variation of intensity from a $22\mu m$ wide, $10\mu m$ deep groove using CO_2 laser radiation. The laser polarisation, as in all these experiments was in the same plane as the silicon and in this case was parallel to the groove. Beyond the specular region the intensity measured with the wire grid polariser (WGP) oriented parallel to the groove, falls gradually with increasing angle until about 30° beyond which it falls very rapidly. Thereafter the signal remains very low and the poor signal-to-noise ratio makes interpretation difficult. To overcome this problem a cooled HgCdTe detector will be used in future experiments. However, the dramatic fall in signal level beyond ~ 30° is compatible with an expected minima in the diffraction pattern due to the width of the groove (10) at approximately 34°. The lower trace in Figure 8 is the intensity profile as measured when the laser beam is incident on the surrounding silicon face rather than the groove; the whole trace has been moved down the picture for the sake of clarity. The lack of comparable non-specular radiation is immediately apparent.

Two traces are shown in Figure 9. The top curve is that shown in Figure 8, with both the laser polarised parallel to the groove and the wire grid polariser in the same orientation. The lower trace is with the WGP rotated so as to be orthogonal to the groove. The ratio between these two curves shows that there is less than 1% depolarisation of the laser beam by the groove when the beam is polarised parallel to the groove. A similar insignificant degree of depolarisation is found if the laser is polarised

orthogonal to the groove. If however the laser beam is polarised at approximately 45° to the groove, significant depolarisation is found (Figure 10). This figure shows the angular distribution of measured signal of the polarised component of the scattered radiation (WGP = 45°), the component parallel to the groove, and the component perpendicular to the groove. The ratio (depolarised component/polarised component) for both the parallel to groove and perpendicular to groove components are shown in Figure 11. As can be seen there is, as expected, approximately equal depolarisation into both directions.

Attempts to measure CO_2 laser radiation scattered from a $4\mu m$ wide groove (depth $22\mu m$) have to date been unsuccessful. Even using a cooled $50\mu m$ HgCdTe detector with a focussing lens in front of it the signal scattered from the groove is only marginally greater than that from the surrounding silicon surface. Figure 12 illustrates this; the top curve is the scattered radiation measured when the laser beam is incident on the groove and the lower one is when the beam is incident on the surrounding silicon. Both results are averaged over one or two degree intervals to improve the signal-to-noise ratio. The lower curve shows the angular distribution of scattered radiation obtained when the silicon target is replaced by a standard conventionally polished gold-coated stainless steel mirror as used in CO_2 laser work. The very much lower level of diffuse scattering is immediately apparent and suggests that the silicon targets should be conventionally polished before attempting to measure the scattering from sub-wavelength sized grooves.

4. CONCLUSIONS

This initial work has established a base-line against which future measurements using a CO_2 laser and sub-wavelength sized structure may be compared. It has been shown using a He-Ne laser that, within experimental limits, there is no discrepancy between the measured angular position of the diffraction minima from a simple deep phase object and those predicted using simple scalar diffraction theory when the probing wavelength is at least six times smaller than the structure. Initial infrared measurements, although limited in sensitivity have also tended to support these findings when the wavelength is increased to only half the structure size. Future CO_2 work will use polished silicon to reduce the scatter from the surrounding silicon and a larger area cooled HgCdTe detector. Finally it should be noted that it has been shown that a simple angular scan of the mean scattered He-Ne laser radiation enables both the width and depth of a deep phase object to be simply determined; this may have some possible application to real-time monitoring of materials processing.

ACKNOWLEDGEMENTS

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[1] Hongo K, IEEE Trans Antennas and Prepag. AP-26, No 3, 494 (1978).

[2] Beckman P, Spizzichino A, The scattering of electromagnetic waves from rough surfaces, Pergamon (1963).

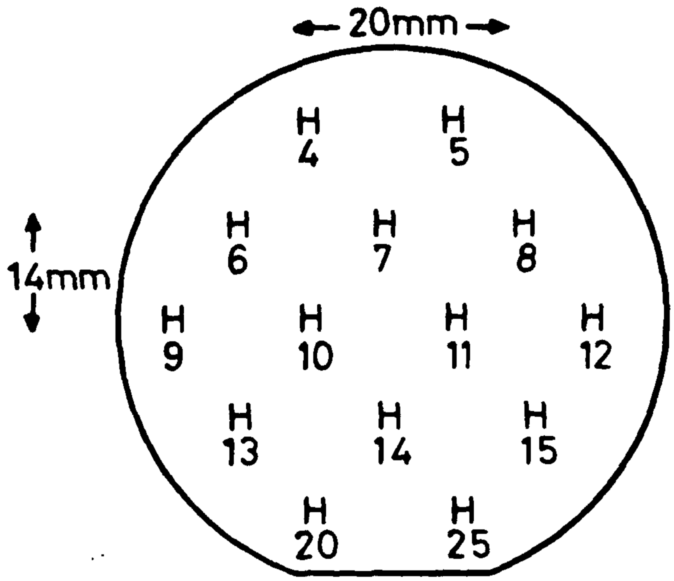

Figure 1(a) Silicon slice showing nominal groove widths.

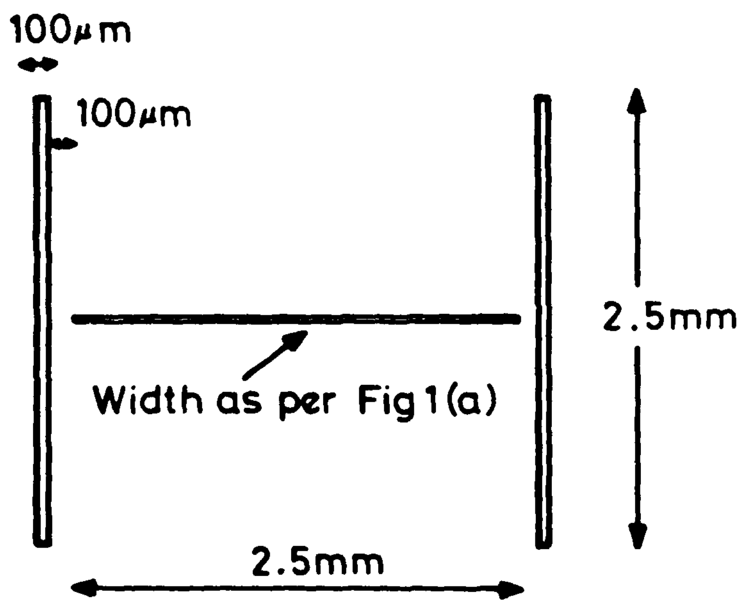

Figure 1(b) Schematic of a single groove showing delineation grooves at sides of it.

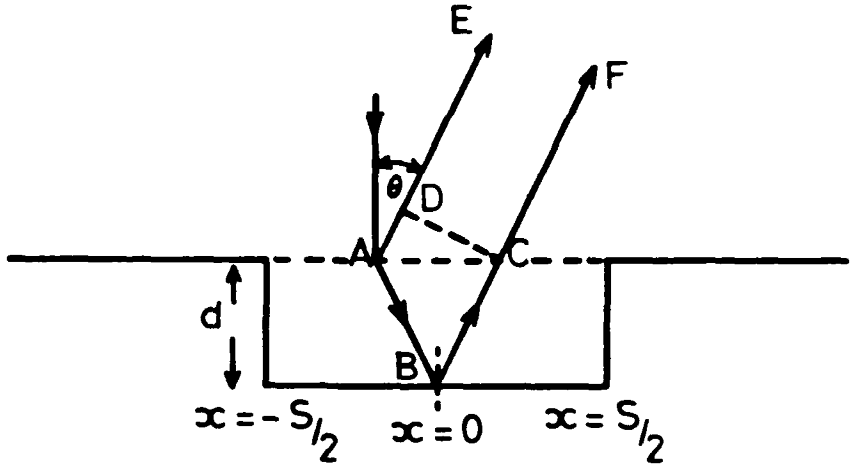

Figure 2 Scattering geometry.

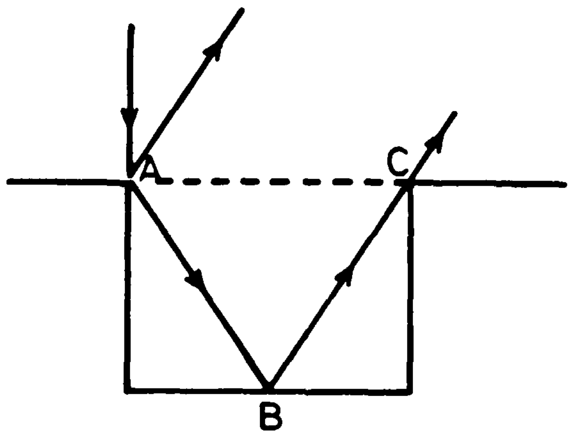

Figure 3(a) Limit of single scattering.

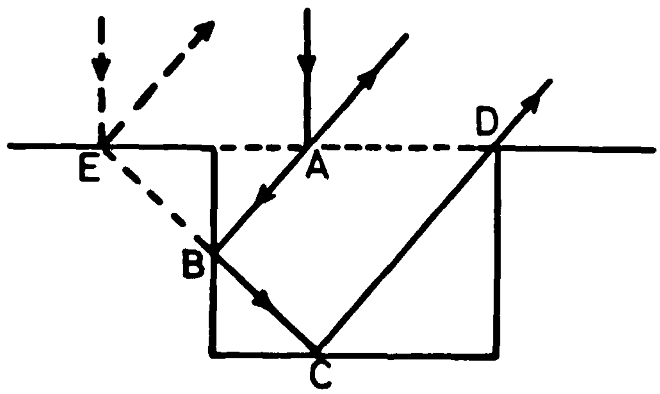

Figure 3(b) Multiple scattering geometry.

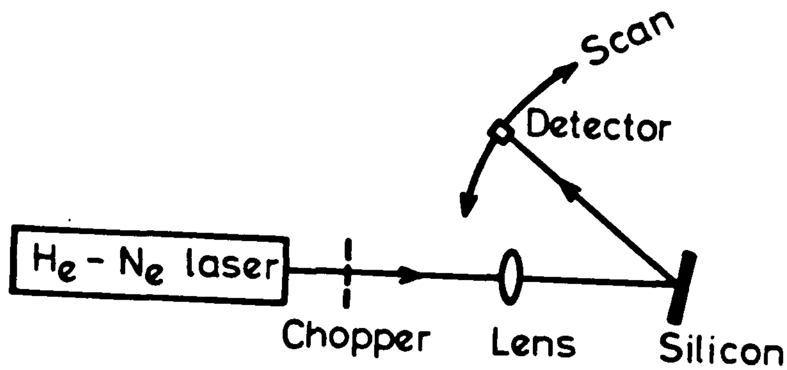

Figure 4 Experimental arrangement.

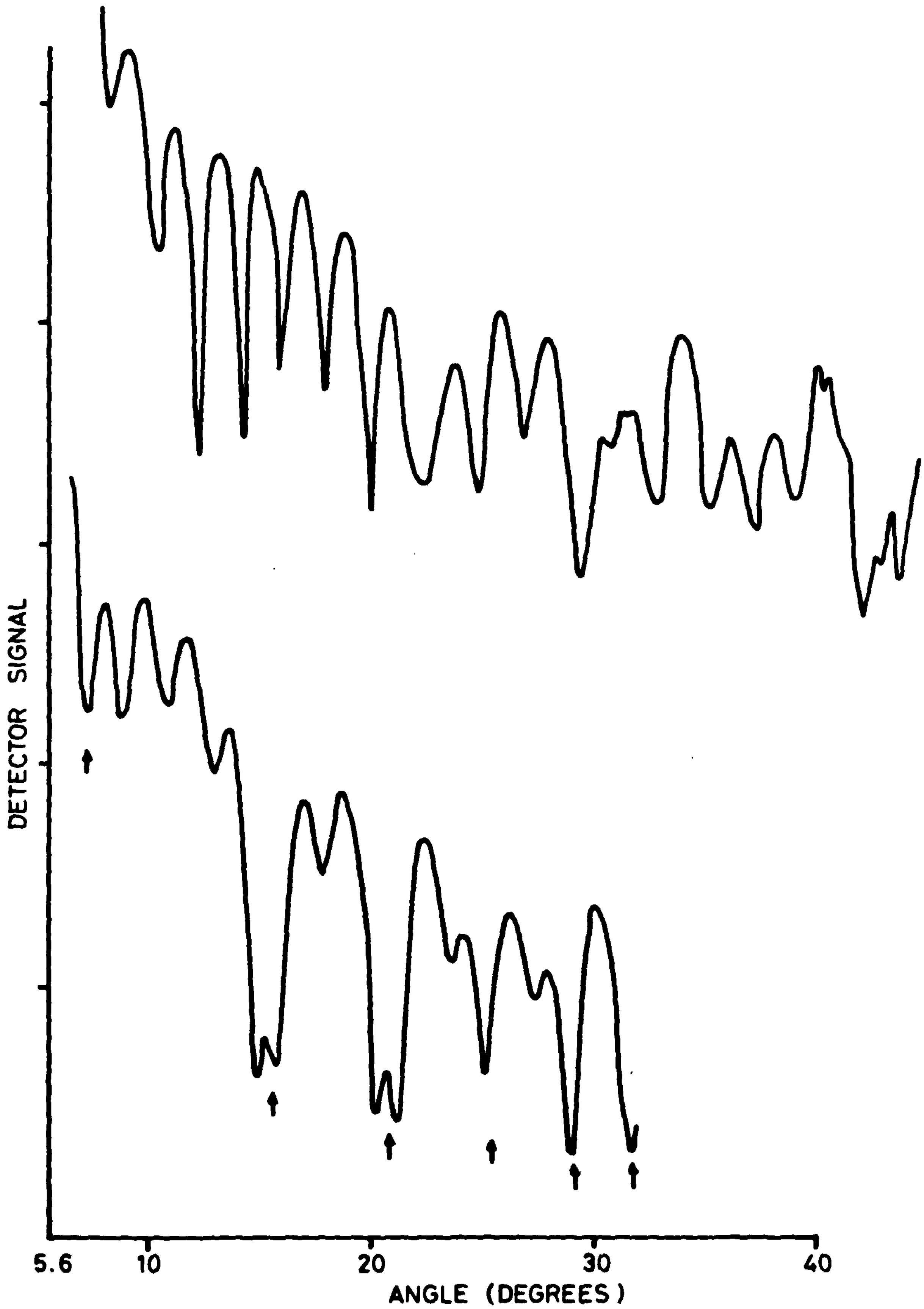

Figure 5 Angular scans. Upper trace – ¼ hour etch; Lower trace – ½ hour etch.

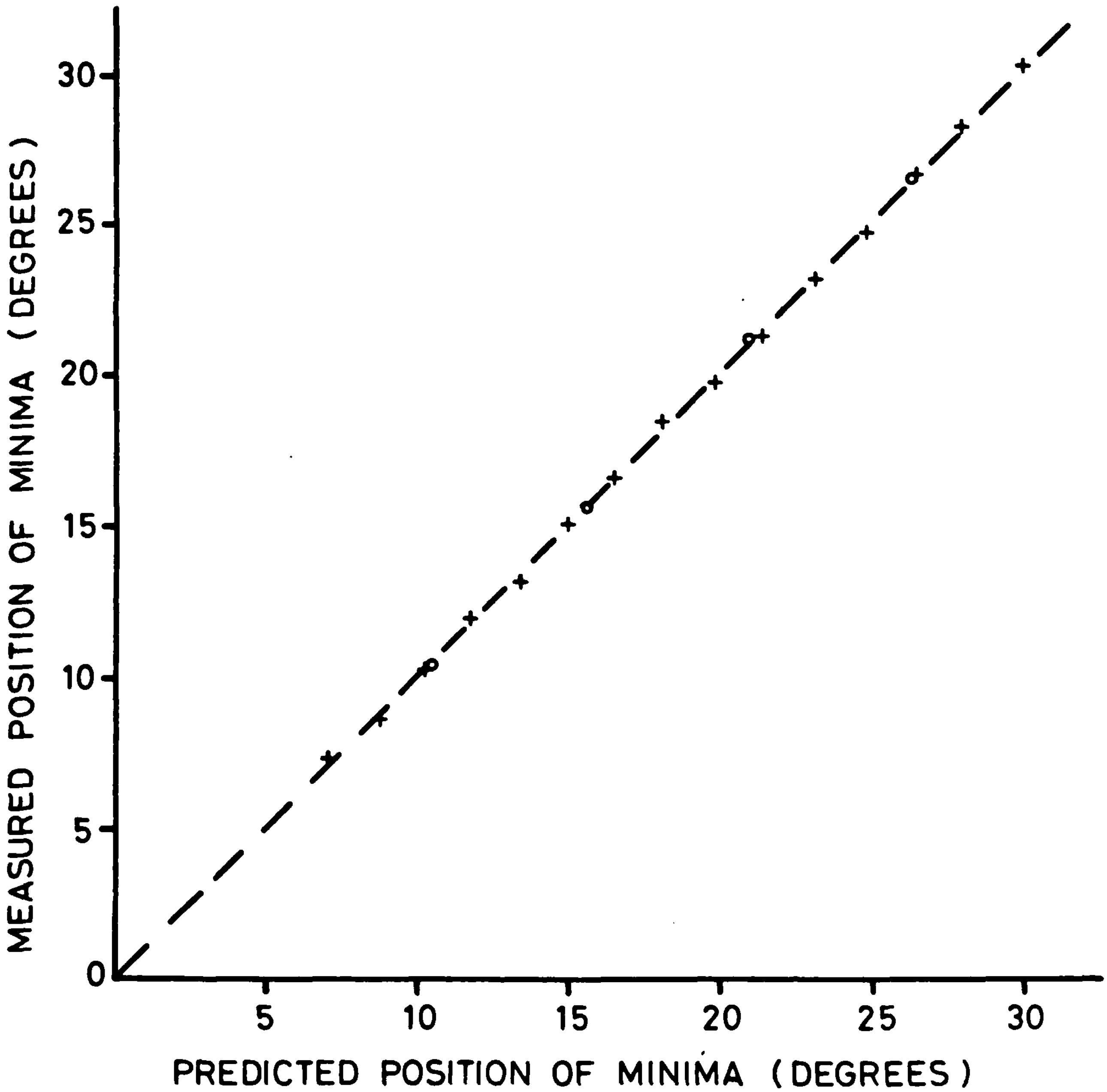

Figure 6 Measured verses predicted angular positions of diffraction minima due to groove width. X - 23.5μm width groove; 0-7.3μm width groove.

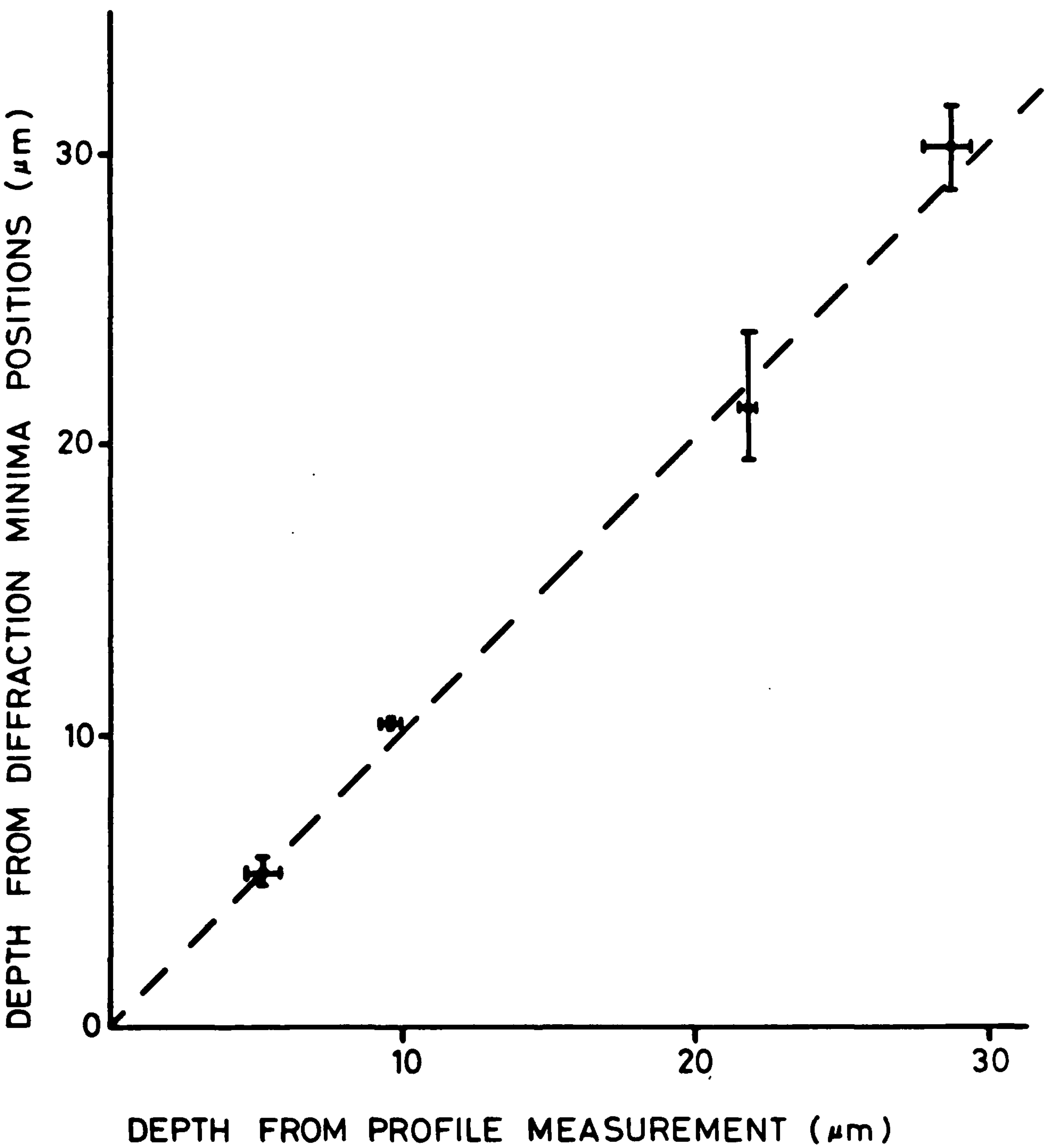

Figure 7 Depth of grooves determined from depth induced diffraction minima verses those determined from profile measurements. Nominal width = 20μm.

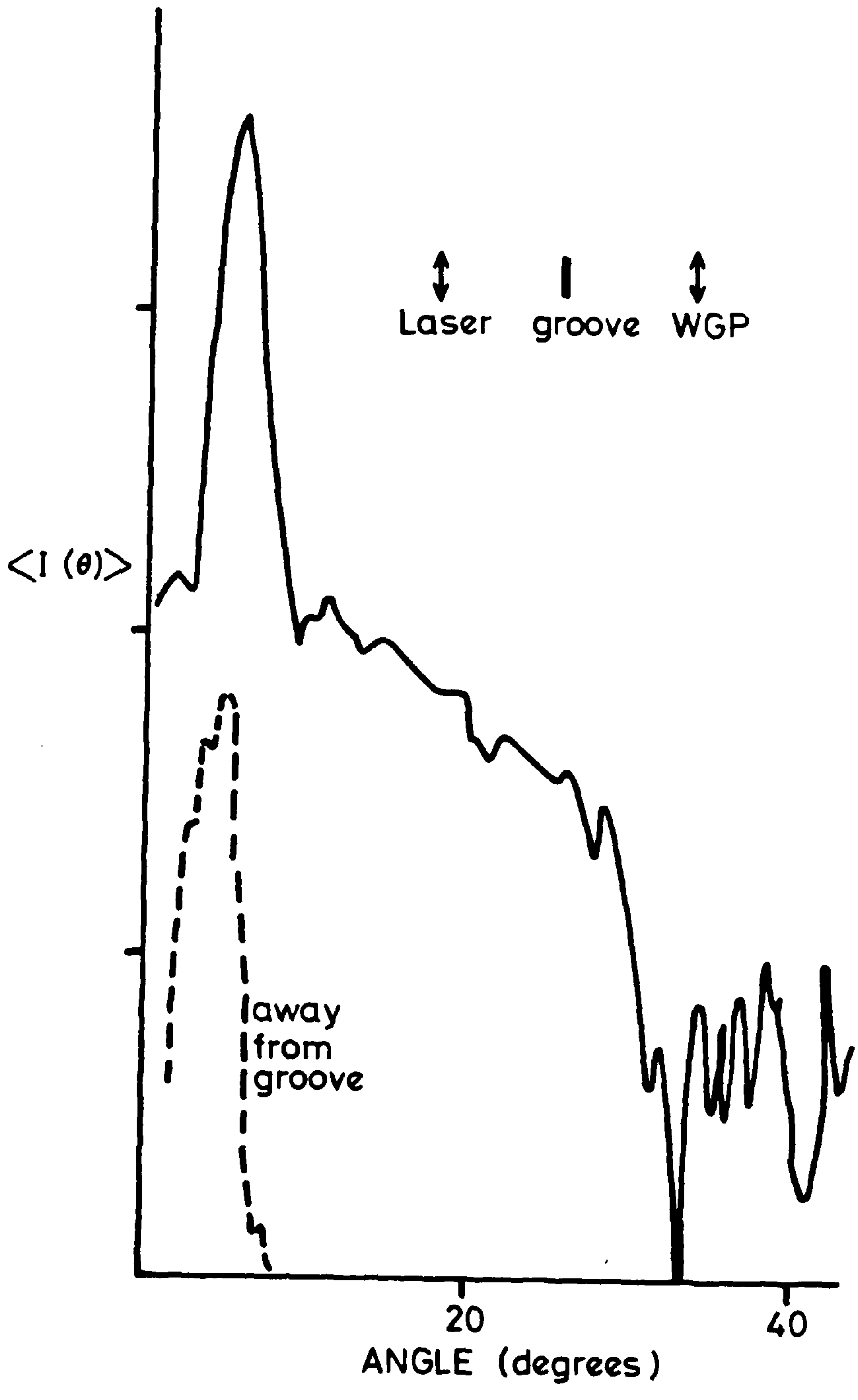

Figure 8 Angular scan using CO_2 laser with laser polarisation direction, groove direction and WGP orientation parallel.

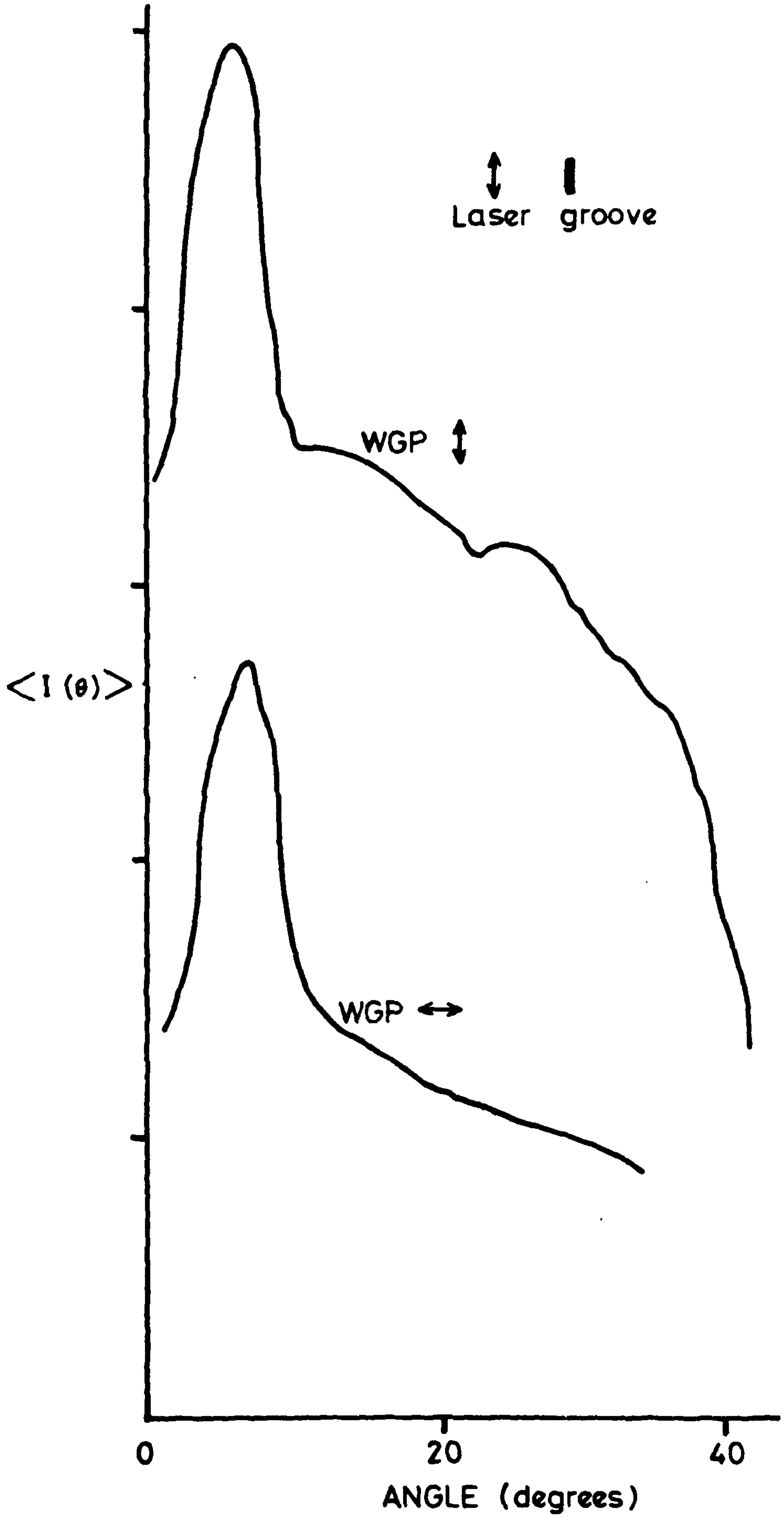

Figure 9 CO_2 laser angular scan with laser polarisation direction parallel to groove. Top trace - WGP parallel to groove. Bottom trace - WGP orthogonal to groove.

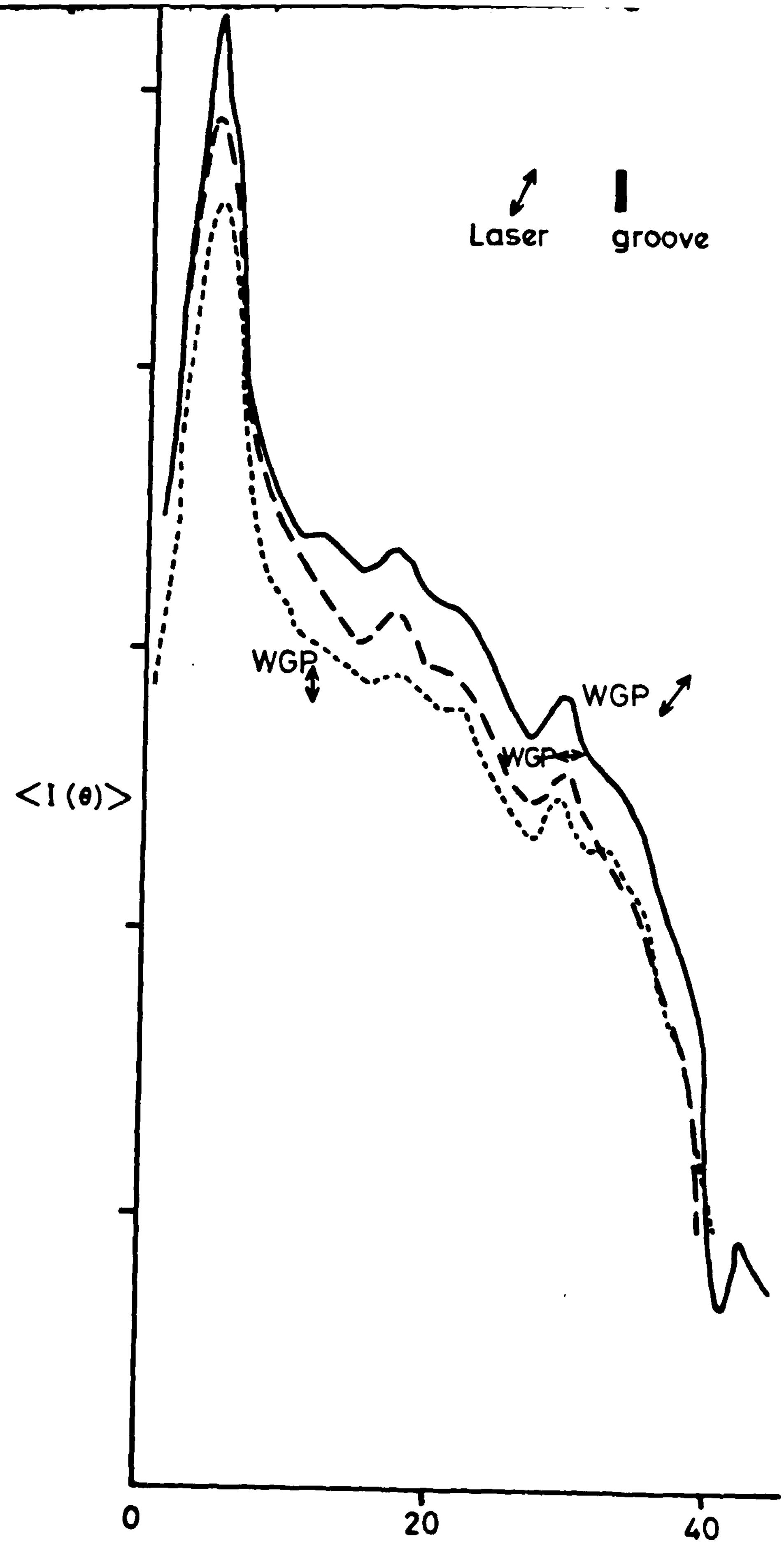

Figure 10 CO_2 laser angular scan with laser polarisation direction rotated 45° with respect to groove direction. —— WGP 45° to groove; --- WGP orthogonal to groove; .... WGP parallel to groove.

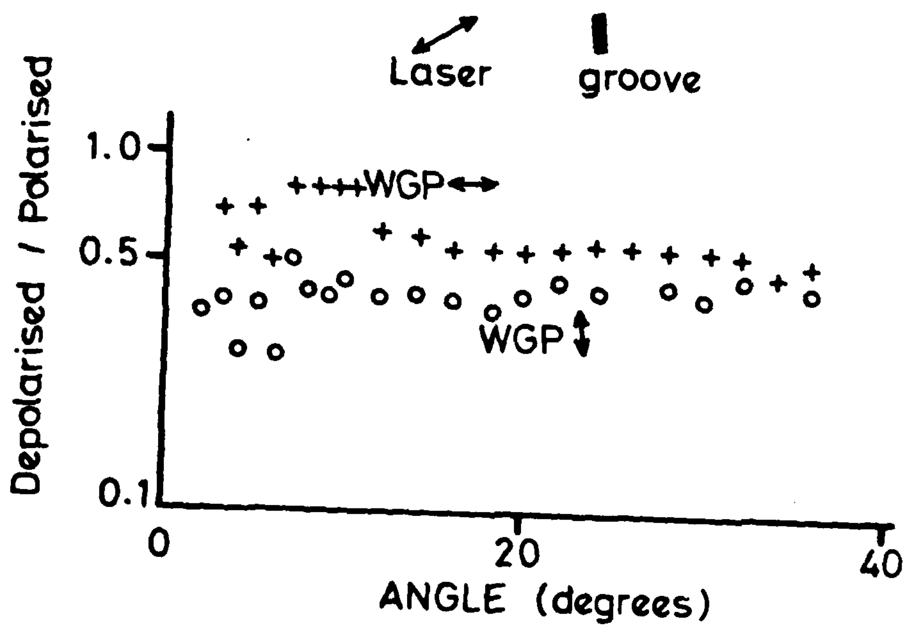

Figure 11 Degree of depolarisation verses angle for case shown in Figure 10.

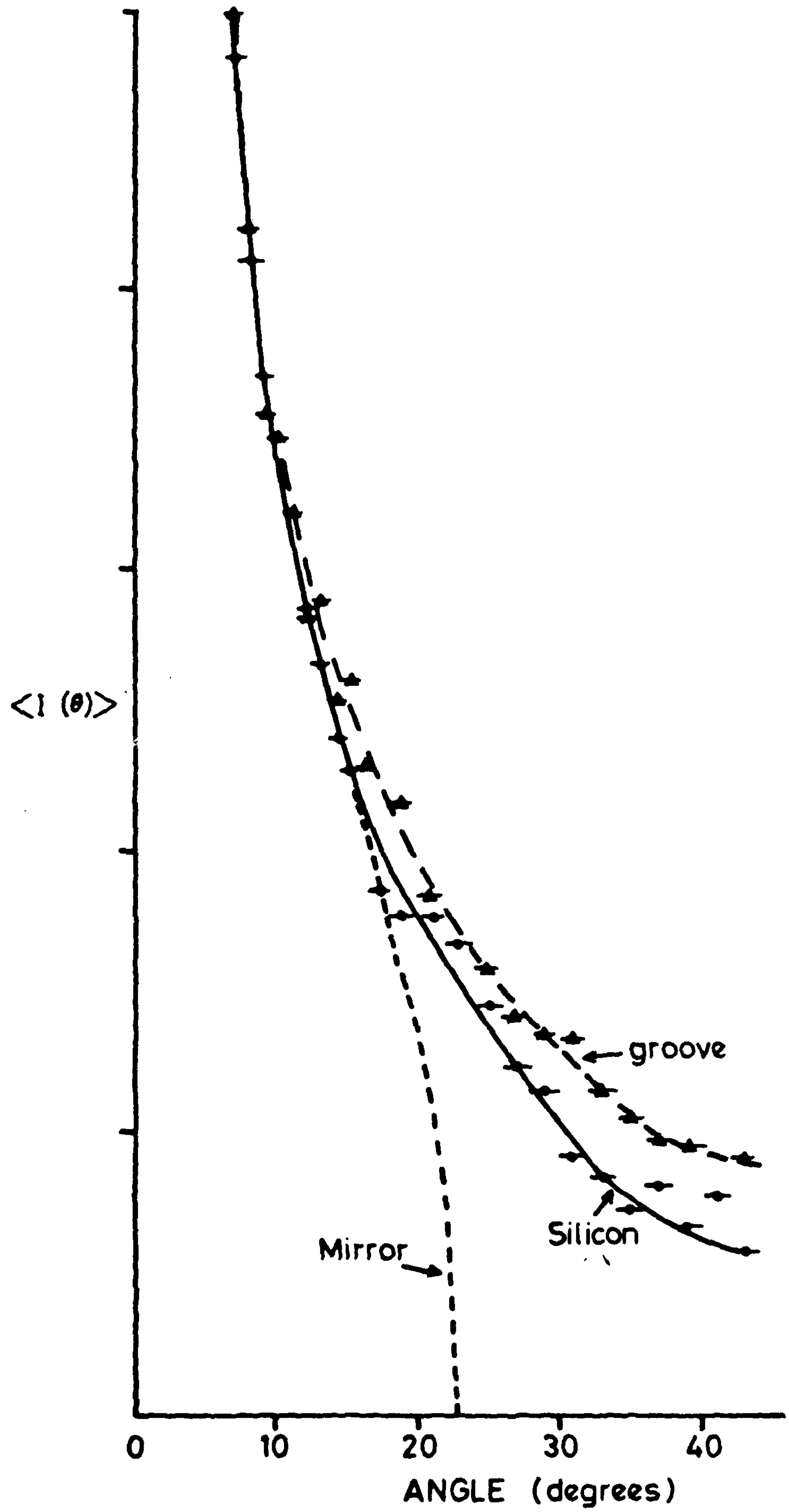

Figure 12 CO_2 laser angular scan using a 4μm wide groove. Top curve – from groove; middle curve – from surrounding silicon; bottom curve – from CO_2 laser mirror.

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Abstract

The work presented in this Memorandum is the first stage in a programme of work designed to study the scattering of radiation from simple phase objects that have dimensions smaller than the wavelength of the probing laser radiation. This initial work establishes the theory and supporting experimental evidence when the structure is somewhat larger than the probing wavelength.

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Figure 3(b) Multiple scattering geometry.